Preliminary design of a 16T cosine theta bending dipole for the Future Circular Collider

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Outline:

1. Main design parameters
2. Magnetic design
3. Mechanical design
4. Protection
5. Conclusions
## 1.1 Main design parameters

<table>
<thead>
<tr>
<th>Constraints for the magnet design</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore inner diameter</td>
<td>50 mm</td>
</tr>
<tr>
<td>Beam distance</td>
<td>250 mm</td>
</tr>
<tr>
<td>Bore nominal field</td>
<td>16 T</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.2 K</td>
</tr>
<tr>
<td>Operation on the load line</td>
<td>90 %</td>
</tr>
<tr>
<td>Maximum strand number per cable</td>
<td>40</td>
</tr>
<tr>
<td>Cable insulation thickness</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>( \text{Cu}/\text{NCu} )</td>
<td>( \geq 1 )</td>
</tr>
<tr>
<td>Field harmonics (geometric/saturation)</td>
<td>( \leq 3/10 ) units</td>
</tr>
<tr>
<td>Peak temperature (105 % of operating current)</td>
<td>350 K</td>
</tr>
<tr>
<td>Yoke outer radius</td>
<td>400 mm</td>
</tr>
</tbody>
</table>

- Magnetic design for a **double aperture** magnet
- Mechanical design for a **single aperture** magnet
1.2 Main design parameters

- \( J_c \) @ 18T, 4.2 K ~890 A/mm\(^2\)
- \( J_c \) @ 18T, 1.9 K ~1500 A/mm\(^2\)
- \( J_c \) @ 16T, 1.9 K ~2250 A/mm\(^2\)
- \( J_c \) @ 16T, 4.2 K ~1500 A/mm\(^2\)
2.1 Magnetic design – cross section

**Cable 1 (inner)**  
Strand number: 28  
Strand diameter: 1.1 mm  
Bare width: 16.5 mm  
Bare inner thickness: 1.892 mm  
Bare outer thickness: 2.036 mm  
Insulation: 0.15 mm  
Keystone angle: 0.5°  
Cu/NCu: 1  
**Operating current**: 10275 A  
**Operating point on LL (4.2 K)**: 90 %

**Cable 2 (outer)**  
Strand number: 38  
Strand diameter: 0.7 mm  
Bare width: 14 mm  
Bare inner thickness: 1.204 mm  
Bare outer thickness: 1.326 mm  
Insulation: 0.15 mm  
Keystone angle: 0.5°  
Cu/NCu: 2.04  
**Operating current**: 10275 A  
**Operating point on LL (4.2 K)**: 90 %

**B peak**: 16.4 T  
**Turn number**:  
Layer 1: 14  
Layer 2: 21  
Layer 3: 37  
Layer 4: 43  
**Tot**: 230/ap.  

**Grading**

All the parameters are within the **designed constraints**

---

4.2 K
2.2 Magnetic design – iron yoke

<table>
<thead>
<tr>
<th>Inductance@I_{op} (1 ap)</th>
<th>Stored energy (1 ap)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mH/m</td>
<td>1.5 MJ/m</td>
</tr>
</tbody>
</table>

Bladder & key
### 2.3 Magnetic design – field quality

**NORMAL RELATIVE MULTIPOLES @ 16 T:**

- $b_1$: 10000  
- $b_2$: -19.94  
- $b_3$: -0.01  
- $b_4$: -0.49  
- $b_5$: 0.97  
- $b_6$: -0.01  
- $b_7$: -0.87  
- $b_8$: -0.00  
- $b_9$: 0.28  
- $b_{10}$: 0.00  
- $b_{11}$: 0.66  
- $b_{12}$: 0.00  
- $b_{13}$: -0.13  
- $b_{14}$: 0.00  
- $b_{15}$: 0.03

- b2 optimization **not yet performed**
- Persistent currents **not** considered

**Acceptable field quality**
2.4 Magnetic design – strand area

Conductor 1:
- 28 strands
- $\varnothing = 1.1$ mm
- Cu/NCu = 1
- $J_{cu} = 934$ A/mm$^2$
- Strand Area = 37.3 cm$^2$/apert.
- Weight (FCC) = 4.3 ktons

Conductor 2
- 38 strands
- $\varnothing = 0.7$ mm
- Cu/NCu = 2.04
- $J_{cu} = 1047$ A/mm$^2$
- Strand Area = 46.8 cm$^2$/apert.
- Weight (FCC) = 5.3 ktons

High Cu content for protection reasons!

COND. AREA (double ap.): = 168.1 cm$^2$

FCC dipoles extrapolation:
- COND. MASS: = 9.6 ktons

<table>
<thead>
<tr>
<th>Data for FCC extrapolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of dipole units</td>
</tr>
<tr>
<td>Dipole length</td>
</tr>
<tr>
<td>Conductor density</td>
</tr>
</tbody>
</table>
2.5 Magnetic design – strand area

➤ Option to reduce cost

**Conductor 2 (smart option)**
- 25 (SC)+13 (Cu) strands
- \( \varnothing = 0.7 \text{ mm} \)
- \( \text{Cu/NCu} = 1 \)
- \( J_{cu} = 1047 \text{ A/mm}^2 \)
- Strand Area (SC)= 30.7 cm\(^2\)/apert.
- Strand Area (Pure Cu) = 16.0 cm\(^2\)/apert.
- SC weight (FCC) = 3.50 ktons
- Pure Cu weight (FCC) = 0.75 ktons
- Pure Cu cost \(<< \) SC cost

➤ Stability as in cable 1 (Cu/NCu = 1)

➤ Current diffusion time in the Cu strands to be evaluated and **compared with discharge time**
  - Zero order evaluation seems **ok** (few ms)

**TOTAL SC STRANDS:** = 9.6 \( \rightarrow \) 7.8 ktons

You can save

\(~\text{20\% costs}\)
3.1 Mechanical design – layout

- The **mechanical** design of the cos-theta option presently **under study**
  exploit the **bladder & key** technology
  - It concerns a **single aperture** producing 16 T central field

![Diagram showing materials used in the design: Al alloy, Titanium, Iron, Copper wedges, Stainless steel]
Due to the very large Lorentz forces, the mechanical structure is based on **3 active elements:**

- Standard **B&D + Al alloy shell** (70 mm thick)
- Tapered **shim** on the midplane
- Ti nose **undercuts**

<table>
<thead>
<tr>
<th>Layer</th>
<th>$\sigma_\theta$ – layer (MPa)</th>
<th>$\sigma_\theta$ – winding (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>layer 1</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>layer 2</td>
<td>101</td>
<td>125</td>
</tr>
<tr>
<td>layer 3</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>layer 4</td>
<td>160</td>
<td></td>
</tr>
</tbody>
</table>
3.3 Mechanical design – accept. criteria

- The acceptance criteria are:
  - Pole-coil contact in pole-turns midpoint: $p_{\text{cont}} \geq 2 \text{ MPa}$
  - Max bladder pressure $< 50 \text{ Mpa}$
  - $\sigma_{\text{equiv coil}} \max \leq 150 \text{ MPa at } 293 \text{ K and } \leq 200 \text{ MPa at } 4.2 \text{ K}$
  - All components $\sigma_{\text{equiv}} \leq$ stress limit
  - For iron at 4.2 K (brittle) $\sigma_1 \leq \sim 200 \text{ MPa}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Stress limit (MPa)</th>
<th>E (GPa)</th>
<th>$\nu$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>293 K</td>
<td>4.2 K</td>
<td>293 K</td>
<td>293 K</td>
</tr>
<tr>
<td></td>
<td>4.2 K</td>
<td></td>
<td></td>
<td>4.2 K</td>
</tr>
<tr>
<td></td>
<td>293 K/4.2 K</td>
<td></td>
<td></td>
<td>293 K/4.2 K</td>
</tr>
<tr>
<td><strong>Coil</strong></td>
<td>150</td>
<td>200</td>
<td>EX=52</td>
<td>EX=52</td>
</tr>
<tr>
<td></td>
<td>EY=44</td>
<td>GXY=21</td>
<td>EY=44</td>
<td>GXY=21</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X=3.1E-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y=3.4E-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Austenitic steel 316LN</strong></td>
<td>350</td>
<td>1050</td>
<td>193</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.8E-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Al 7075</strong></td>
<td>480</td>
<td>690</td>
<td>70</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.2E-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ferromagnetic iron</strong></td>
<td>180</td>
<td>720</td>
<td>213</td>
<td>224</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0E-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pole (Ti6Al4V)</strong></td>
<td>800</td>
<td>1650</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.7E-3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.4 Mechanical design – pole-coil contact

- The plots represent the contact pressure [MPa] at the pole-coil interfaces
  - Third layer is not optimal, even if in its midpoint \( p_{\text{cont}} \geq 5 \text{ MPa} \)

![Pressure plots](image)

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Cool-down</th>
<th>Energization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure [MPa]</td>
<td>Pressure [MPa]</td>
<td>Pressure [MPa]</td>
</tr>
</tbody>
</table>

Vittorio Marinozzi, FCC week, 13/04/2016, Rome
3.5 Mechanical design – Von Mises stress

- The stress in the windings has **not been optimized** yet

  - The grey regions **overcome** 150 MPa at 293 K and 200 MPa at 4.2 K
3.6 Mechanical design – $\sigma_1$ in iron yoke

- At cold iron is supposed to become **brittle**. A safe condition is $\sigma_1 < 200$ Mpa
  - The resulting stress can be limited by **increasing the curvature** radius where the peaks are located
3.7 Mechanical design –
Von Mises stress in components

- Except iron, the Von Mises stress of all material is **below** the corresponding stress limit

<table>
<thead>
<tr>
<th>Material</th>
<th>Assembly [MPa]</th>
<th>Cool-down [MPa]</th>
<th>Energization [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td>668</td>
<td>1150</td>
<td>613</td>
</tr>
<tr>
<td>Iron</td>
<td>381</td>
<td>451</td>
<td>553</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>734</td>
<td>859</td>
<td>1010</td>
</tr>
<tr>
<td>Al alloy</td>
<td>47</td>
<td>168</td>
<td>167</td>
</tr>
</tbody>
</table>
4.1 Protection

- Main assumptions:
  - **No** energy extraction
  - Quench induced in the whole magnet 40 ms after initial quench start
  - Inductance dependence on the current
  - Material properties from NIST

- Results (105% of \( I_{op} \)):
  - Hot spot temperature: \(~330\,\text{K}\)
  - Maximum voltage to ground: \(~1400\,\text{V}\)

More details in the Tiina Salmi talk
5.1 Conclusions

- The presented 16 T cosine-theta **accomplishes** the Eurocirccol design constraints
  - Margin on the load-line is **90%** at 4.2 K
  - Good **field quality**
  - Hot spot temperature **below 350 K** @ 105% $I_{op}$

- Main **cosine-theta advantage**: **less conductor area, less costs**
  - 168.1 cm²
  - Possibility of using **pure copper strands** in order to save **~20%** of SC strands

- **Bladders and key** mechanical structure
  - Needed **pre-stress** can be **hardly achieved** @ $I_{op}$
  - Stress on the conductor **too high** in some zones, mainly during **assembly**
  - To be **improved**, **work in progress**